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A methodology to link national and local information for spatial targeting of ammonia mitigation efforts

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Abstract

The effects of atmospheric nitrogen (N) deposition are evident in terrestrial ecosystems worldwide, with eutrophication and acidification leading to significant changes in species composition. Substantial reductions in N deposition from nitrogen oxides emissions have been achieved in recent decades. By contrast, ammonia (NH_3) emissions from agriculture have not decreased substantially and are typically highly spatially variable, making efficient mitigation challenging. One solution is to target NH_3 mitigation measures spatially in source landscapes to maximize the benefits for nature conservation. The paper develops an approach to link national scale data and detailed local data to help identify suitable measures for spatial targeting of local sources near designated Special Areas of Conservation (SACs). The methodology combines high-resolution national data on emissions, deposition and source attribution with local data on agricultural management and site conditions.

Application of the methodology for the full set of 240 SACs in England found that agriculture contributes ~45 % of total N deposition. Activities associated with cattle farming represented 54 % of agricultural NH_3 emissions within 2 km of the SACs, making them a major contributor to local N deposition, followed by mineral fertilizer application (21%). Incorporation of local information on agricultural management practices at seven example SACs provided the means to correct outcomes compared with national-scale emission factors. The outcomes show how national scale datasets can provide information on N deposition threats at landscape to national scales, while local-scale information helps to understand the feasibility of mitigation measures, including the impact of detailed spatial targeting on N deposition rates to designated sites.

Keywords: ammonia; dry deposition; emission abatement; nitrogen; UK

1. Introduction

Atmospheric nitrogen (N) deposition is an international issue, with effects of eutrophication and acidification evident worldwide. Throughout Europe, increases in N deposition have resulted in changes to species composition, with declines in N-sensitive species at the expense of a smaller number of fast growing species that favour high N supply (Dise *et al.*, 2011). Thresholds of N deposition are currently exceeded in > 50 % of Europe, and will continue to be exceeded under current projections of N emissions (Hettelingh *et al.,* 2008). In the UK, N deposition is estimated to have almost doubled throughout the 20th century (Fowler *et al.*, 2004), with increased emissions of nitrogen oxides (NO_x, mainly from motorised transport, power generation and other combustion sources) and ammonia (NH_3, mainly from agricultural sources). Although substantial efforts in UK and European policies in recent decades have led to a considerable reduction in NO_x emissions (RoTAP, 2012), much less has been achieved in reducing NH_3 emissions. Around 82 % of UK NH_3 emissions are estimated to derive from agriculture (Misselbrook *et al.*, 2013). As these are typically diffuse sources, it has sometimes been argued that it is much harder to implement emission controls, compared with NO_x, which is often associated with point sources (RoTAP, 2012). However, in the UK there has also been a low political willingness to implement NH_3 control measures in agriculture, compared with other countries, such as the Netherlands and Denmark, which have made more progress in reducing emissions (Sutton *et al.* 2003; Bleeker *et al.* 2009, e.g. Jimmink *et al.*, 2014; NERI, 2007).

A wide range of potential mitigation measures exists to reduce NH_3 emissions from agricultural sources. Measures to reduce N deposition include both source-oriented technical measures, which aim to minimise emissions at source (e.g. covering slurry stores; Bittman *et al.*, 2014) and landscape-oriented measures. Landscape-oriented measures aim to optimise spatial relationships between emission sources and sensitive habitats. Such measures include minimising agricultural activity around sites (e.g. controlling spreading within buffer zones close to the sensitive habitat areas) or planting trees to recapture and disperse emissions (e.g. Dragosits *et al.*, 2006; Bealey *et al.*, 2016). Under current rates of N deposition, it is estimated that around 60 % of SACs (European Commission, 2016) remain under substantial threat, with thresholds for atmospheric N pollution effects exceeded both in the case of critical loads for total nitrogen deposition (Hall and Smith, 2015) and for critical levels for NH_3 concentrations (e.g. Hallsworth et al., 2010; Vogt *et al.*, 2013).

Concentrations of NH_3 (and subsequent deposition of reactive N) from agricultural sources are highly spatially variable (e.g. Vogt *et al.*, 2013; Dragosits *et al.*, 2002; Sutton *et al.*, 1998) making it challenging to avoid critical load and critical level exceedance across all designated sites at a national scale. This highlights the need to interface national level and local level strategies. In particular, to reduce N deposition effectively at designated sites, areas of high NH_3 concentrations need to be reliably identified, which can allow NH_3 mitigation measures to be targeted spatially to the most critical locations (e.g. Dragosits *et al.,* 2002; Theobald *et al.,* 2004; Dragosits *et al.,* 2006; Hallsworth *et al.*, 2010).

This paper presents an approach for identifying the main sources of N deposition at Natura 2000 sites and ascertain the most effective measures to target local decreases of deposition at each site. It focuses on where to apply NH_3 mitigation measures rather than an analysis of the different abatement measures themselves. This paper's focus is on the case of protecting Special Areas of Conservation (SACs), but the approach is generally applicable to other regions and natural habitat designations. The methodology is first applied to all 240 SACs in England by applying national datasets. It is then applied by combining national and local datasets for seven example SACs to provide insights on how local information can help refine the assessment.

2. Methods

The main emission sources contributing to N deposition were identified for each SAC in England, which are part of the European Union's Natura 2000 network. NH_3 emissions were also estimated in areas up to 2 km surrounding each site, and in more detail for agricultural sources, which are the largest contributor of NH_3 emissions. In addition, seven sites were assessed in more detail, to establish whether supplementary local data (e.g. the direction of prevailing winds) and refinements to the methodology could lead to improved targeting of measures. Figure 1 illustrates the draft framework devised to assess designated sites for N threats.

<< FIGURE 1 >>

Figure 1. Draft framework for assessing N threats at designated sites (adapted from Dragosits *et al.*, 2015a)

The datasets used to determine the threat of atmospheric N input to sensitive protected features at SACs include: i) modelled atmospheric concentration and deposition data; ii) high-resolution agricultural statistics for livestock numbers and crop areas; iii) farm management and practice information; iv) aerial images; and v) meteorological data. A draft framework for the approach used is summarised in Figure 1. The following sub-sections outline how this framework may be applied and how national and local information sources have been used to assess N deposition threats to designated sites in England.

2.1. Data sources

National data sets

The main emission sources contributing to N deposition at each SAC were estimated using modelled source attribution data. Source attribution data are derived by performing multiple model runs of an atmospheric transport and deposition model, with each source type removed in turn. N deposition attributed to individual emission source categories (such as agriculture, road transport etc.) or individual large point sources (such as power stations) can then be calculated as a proportion of total deposition to each model grid square.

In this study, N deposition estimates for the year 2005 were produced at a 5 km grid resolution using the Fine Resolution Atmospheric Multi-pollutant Exchange model (FRAME, e.g. Dore *et al.*, 2014; Bealey *et al.*, 2014). FRAME is a Lagrangian atmospheric chemistry transport model with the relevant atmospheric processes (vertical diffusion, chemical transformation, wet and dry deposition) calculated in a moving vertical column of air comprising 33 layers with a variable layer depth from 1 m at the surface to 200 m for the upper layer. The model utilises emission estimates of NH_3, NO_x and SO_2, to calculate atmospheric concentrations of gases. Chemical reactions include both aqueous and dry phase oxidation and the conversion of gases to form particulate matter (ammonium sulphate and ammonium nitrate). Long range transport is driven by year specific wind direction and wind speed frequency roses (Dore et al, 2006) The model uses a resistance analogy within a 'big leaf model' to calculate the dry deposition velocity of gases and particulates to vegetation (Smith *et al*, 2000). Wet deposition is calculated using scavenging coefficients combined with annual precipitation estimates based on the UK Met Office national precipitation monitoring network. Deposition estimates are calculated for different vegetation types including forest, moorland, grassland, arable, urban and water. The boundary conditions for the concentrations of pollutants in air used to initialise a UK simulation were calculated with a larger scale European simulation using a 50 km grid resolution and emissions from the EMEP database (http://www.ceip.at). The model has been used to calculate historical and future trends in sulphur and nitrogen deposition as well as the exceedance of critical loads (Matejko *et al,* 2009). Source-receptor relationships generated by the model were used in integrated assessment modelling to determine cost-effective emission abatement strategies to protect natural ecosystems and human health (Oxley *et al*, 2013)

Comparison of the modelled concentrations of gases and particulates in air and of sulphur and nitrogen compounds in precipitation with measurements from the national monitoring networks demonstrated that the model was 'fit for purpose' and performed well in comparison with other atmospheric chemical transport models (Dore *et al.*, 2015). These data incorporate UK estimates of NO_x and NH_3 emissions (National Atmospheric Emission Inventory (NAEI), www.naei.org.uk), with agricultural emissions distributed using the AENEID model (e.g. Dragosits *et al.* 1998). N deposition estimates from 160 source categories (e.g. including agriculture, road transport, shipping, industry) were used in this study.

In addition, high-resolution agricultural census data were used to provide information on livestock numbers and crop areas for characterising key local emission sources and emission densities in the vicinity of SACs. The English agricultural census contributes to the EC Farm Structure Survey (FSS), which gathers information on livestock numbers and crop areas from individual agricultural holdings for each of the 27 EU member states every 10 years. The 2013 agricultural census data used here were supplied at a holding level by the Department for Food and Rural Affairs (Defra) and is based on a survey of between ~50,000 holdings a year, with a full census carried out every 10 years (Defra, 2013). For holdings where no survey is carried out, values are imputed based on the survey data received and corresponding trends derived from these and previous data available for these holdings.

Data on the occurrence of large pig and poultry farms were available from the register of permits under the Industrial Emissions Directive (IED; European Comission, 2016b), which applies to farms with > 40,000 places for poultry, > 2,000 places for production pigs (> 30 kg) or > 750 places for sows. In contrast to the agricultural census data (at the holding level), the location and capacity of these farm is freely available to the public. Ordnance Survey “Strategi” data were used to determine the proximity of SACs to major roads (https://www.ordnancesurvey.co.uk/business-and-government/products/strategi.html).

Local data sources

Seven sites were further assessed, using more detailed local data sets. These sites were Birklands and Bilhaugh SAC (53.204 N, 1.075 W), Culm Grasslands SAC (50.980 N, 3.647 W), Ingleborough Complex SAC (54.160 N, 2.373 W), Mole Gap to Reigate SAC (51.265 N, 0.280 W), North York Moors SAC (54.409 N, 0.904 W) and Walton Moss SAC (54.990 N, 2.775 W).

At these sites, Google Earth imagery was used to identify potential additional sources and provide further information on the sources already identified. Areas with high NH_3 concentrations were identified using 1 km grid resolution NH_3 concentration data (1 km grid version of FRAME). Wind statistics taken from weather stations nearby to each of the sites (windfinder.com) were used to assess local wind conditions (where available). Findings from a parallel study by Misselbrook *et al.* (2015) were used to assess agricultural management practices in the areas surrounding some of the sites.

2.2. Identifying main emission sources contributing to N deposition at a site

All SACs were assessed to determine the main sources of N deposition received by a given site. The source attribution dataset was used to help characterise sites, based on the origin of the N deposition they were estimated to receive. At SACs that intersect multiple 5 km source attribution grid squares, the intersecting grid square with the highest total N deposition estimate was used based on the requirement of the Habitats Directive to adopt a precautionary approach, as there is no dataset available with the location of designated features within UK SACs. The emission sources used in the FRAME model were aggregated into the following broader source categories:

a) **Lowland agriculture (many diffuse sources):** Emissions associated with livestock farming and mineral fertiliser application were considered a main source of N deposition where deposition from all agricultural sources contribute > 20 % of total N deposition.
b) **Vicinity of Large intensive pig and poultry farms:** Intensive agriculture was considered a main potential source of N deposition at sites within 2 km of an intensive pig/poultry farm above the threshold for the Industrial Emissions Directive and where > 20 % of N deposition originated from agricultural activities.

c) **Non-agricultural (point) source(s):** Non-agricultural emissions were considered a main source of N deposition where deposition from such sources contributes > 20 % of total N deposition. These sources include emissions from point combustion sources (such as energy production, refineries), international shipping, non-road transport (i.e. rail, local shipping, air travel), and non-agricultural NH_3 sources (such as pets, wild animals, sewage sludge, composting, household products, humans, and landfill).

d) **Vicinity of major roads:** Road traffic was considered a main contributor to N deposition if it accounted for > 10 % of total N deposition to the relevant grid square and if a main road (motorway, primary or A-road) was within 200 m of the SAC boundary.

e) **Remote (upland) sites affected by long-range N input:** N deposition was considered a regional issue when wet deposition was > 40 % of total N deposition received by a site.

The 200 m road threshold was based on the findings in Cape *et al.* (2004), who suggest that local enhancement of NO_x and NH_3 concentrations near roads is limited to within 200 m. A threshold of 10 % of total N deposition was used for road transport, rather than the 20 % threshold used for other sources, as deposition from road transport does not typically account for a large proportion of the total N deposition to a 5 km grid square, due to their linear nature.

2.3. Quantifying high-resolution agricultural emissions

In an additional analysis, agricultural NH_3 emissions were estimated for the area surrounding each of the designated sites, using 2012 agricultural census data. Buffer zones around each of the SACs were created to estimate the agricultural NH_3 emission density for the immediate area surrounding all the SACs in England, indicating the average intensity of the N-emitting agricultural activities, and to determine all major agricultural sectors contributing to emissions within this zone. A buffer zone of 2 km has been used in this study, to quantify agricultural emissions around each site. The value of 2 km was selected, as it is the approximate distance from a medium-large poultry farm (e.g. 400,000 laying hens) beyond which the contribution of the poultry farm was marginal compared with the contribution of other sources in a mixed agricultural landscape (Dragosits *et al.* 2006). Additionally a 2 km buffer zone is used when regulating (IED) farms in the UK, with farms required to conduct a detailed impact assessment when they are within 2 km of a designated site (Environment Agency, 2005).

UK average NH_3 emission factors (EFs) from the agricultural emission inventory (Misselbrook *et al.*, 2013) were applied at the holding level data to estimate emission densities surrounding each SAC. Agricultural NH_3 emissions were estimated separately for mineral fertiliser and livestock sources. Emissions from livestock sources include all emissions associated with livestock and manure management (i.e. housing, grazing, manure storage and spreading). In order to comply with the data license agreement for this study model results were aggregated to show results that refer to at least five agricultural holdings. In extensive agricultural regions, where this requirement was not met with the standard 2 km buffer zone, the zone around the SAC boundary was increased in size to include additional agricultural holdings until the disclosivity criterion was met. The 2 km zone of influence had to be extended for 9 % of the SACs studied, to a maximum of 5 km.

2.4. Detailed, site-level analyses

Seven example SACs were assessed in more detail, in addition to the modelling carried out for all SACs (as discussed in previous sections). This more detailed analysis was carried out to establish whether supplementary data (e.g. the direction of prevailing winds) and further refinement of the methodology (e.g. considering constituent parts of each site individually) could lead to improved targeting of measures. In summary, the following methodological refinements were made:

- As some SACs are very large (> 1,000 km^2) and complex (consisting of multiple spatially separate parts, sometimes separated from each other by 10s of kilometres), sites were re-assessed at the sub-site level, using individual 5 km grid source attribution estimates, which intersect the SAC.
- Detailed management information from nearby IED pig/poultry units (<2 km away) was used to estimate the contribution of individual IED farms to N deposition and NH_3 concentrations at the sub-sites.
- High spatial resolution (1 km grid resolution) NH_3 concentration data allowed source areas (e.g. dominated by diffuse agriculture) to be separated from semi-natural NH_3 sink areas more successfully than at the 5 km grid resolution. This therefore allowed a more realistic quantification of NH_3 concentrations at a site.
- Arial imagery was used in conjunction with the national datasets, to estimate distances of sources from the site boundary and to make a visual assessment of local conditions.
- Local prevailing wind conditions were determined, to give a higher weighting to sources upwind of a site.
- Local information on agricultural management practices was used to compare site-specific emission estimates (based on local data) to those allocated using UK average EFs. This additional information on farming practice included livestock housing systems and duration of housing season, locations and properties of manure storage systems and land spreading methods used. This information was collected for farms surrounding two of the sites, Culm Grasslands and Cerne & Sydling Downs and was used to produce more detailed emission estimates than by applying national average emission factors that include a mix of systems present

In addition to the methodological refinements listed above, results for these sites were also validated by the site-officers responsible for each site.

3. Results

The source attribution analysis indicates that the majority of SACs in England receive a substantial amount of their atmospheric N deposition from diffuse agriculture and non-agricultural (point) emission sources (Figures 2 and 3); with nearly all sites affected by these, two source types. Of the sites that receive substantial amounts of N deposition from agricultural sources, approximately 20% of English SACs are within 2 km of an IED-regulated intensive pig/poultry farm. Road transport is estimated to be a main source of N deposition at ~13 % of sites with low growing semi-natural features and ~30 % of sites with woodland features. Long-range transport of N deposition is estimated to be a main source at ~60 % of sites with low-growing semi-natural features and ~30 % of sites with woodland features.

<< FIGURE 2 >>

Figure 2 – Main contributors to N deposition at Special Areas of Conservation (SACs) in England (*n* = 240) from national scale source attribution data (5 km grid) using N deposition estimates to semi-natural features and proximity of sites to IED poultry farms data (2 km radius) and major roads (200 m radius). The category 'non-agricultural (point) source(s)' shown in this map does not include a local distance criterion.

<< FIGURE 3 >>

Figure 3 – Histogram showing the main source sectors contributing to N deposition at every SAC site in England (*n* = 240), derived from source attribution output from the FRAME model. Results are shown separately for low-growing semi-natural features (light grey) and woodland features (black) due to different N deposition velocities.

3.1. Agricultural NH_3 emissions

A substantial proportion (66 sites) of SACs in England are estimated to be subject to NH_3 emission densities of > 10 kg N ha^{-1} yr^{-1} originating from agricultural activities close to their site boundary (< 2 km, Table 1). The largest contributor to agricultural NH_3 emissions within the 2 km buffer zone of sites, on average, is cattle farming (~52 %). Sites with high emission densities (> 10 kg N ha^{-1} yr^{-1}) tend to be associated with emissions from dairy farming, in particular.

The spatial correlation between cattle farming areas and locations of SACs is also apparent from the analysis of agricultural source categories shown in Table 1. The 2 km areas surrounding England's SACs, appear to have higher emissions associated with cattle farming, when compared with agricultural emissions for England as a whole. This may be because a large proportion of SACs are situated in lowland regions, which typically are associated with cattle farming. Apart from cattle, the application of mineral fertilizers (especially urea) is the next most important source category (Table 1), both for England as a whole and within 2 km distance of SACs. Only if a much higher emission threshold is used do pig and poultry contribute to a larger proportion to the emissions. For example, for locations with >30 kg N ha^{-1} yr^{-1} (~3 % of England's SACs), pigs contribute 12.5 % and poultry contribute 18.1 % of the emissions.

Table 1 – Proportion of agricultural NH_3 emissions by sector 2012 (using emission factors from Misselbrook *et al.* 2013). Sectors that are estimated to exceed 15% of total emissions are shown in bold (N.B. percentages may not add up to 100 % due to rounding).

		Proportion of estimated agricultural NH_3 emissions (%)						
Emission Area	*n*	Dairy Cattle	Other Cattle	Sheep	Pigs	Poultry	Fertiliser Application	Other Livestock
England	NA	**25**	**21**	3	10	15	**24**	2
Within 2 km of England's SACs	240	**27**	**27**	5	8	10	**21**	2
Within 2 km of England's SACs, with agricultural NH3 emission density < 10 kg N ha-1 yr-1	174	**16**	**29**	8	7	8	**29**	3
Within 2 km of England's SACs, with agricultural NH3 emission density > 10 kg N ha-1 yr-1	66	**35**	**25**	3	9	11	**15**	1
Within 2 km of England's SACs, with agricultural NH3 emission density > 30 kg N ha-1 yr-1	6	**44**	**16**	0	13	**18**	9	0

The northwest and southwest of England especially appear to have high agricultural emission densities, originating from activities associated with cattle farming near designated sites (Figure 4). In contrast, the southeast and east of England, where much of England's intensive pig and poultry farming is situated, cattle farming contributes to a smaller fraction of total agricultural emissions.

<< FIGURE 4 >>

Figure 4 – Estimated agricultural NH_3 emission source apportionment for all SACs in England. The size of each pie chart is proportional to the estimated local NH_3 emission density surrounding each site (< 2 km from SAC boundary). The category 'other agriculture' refers to fertiliser and livestock sources other than cattle. At sites with fewer than five cattle holdings within the 2 km buffer zone surrounding the site boundary, the category 'total agriculture' is used to show the estimated emission density from all agricultural sources in order to maintain farm anonymity.

3.3. Local scale assessment

The local scale analysis shows sub-site variability in N deposition at sites that intersect multiple model grid squares (Table 2). The proportion of N deposition originating from agricultural sources is also highly variable across sites. In this paper, the results for Culm Grasslands SAC are presented in full and results from the other six sites summarised in Section 3.4.

Table 2 – Summary statistics for the SACs selected for local scale assessment (further details given in Dragosits *et al*. 2015b)

SAC name	Total N Deposition kg N ha^{-1} yr^{-1}	Proportion of N deposition from agricultural sources (%)	Emissions from cattle (% of total agricultural NH_3 emissions)
Birklands and Bilhaugh	34.4	34	43
Cerne and Sydling Downs	24.2 – 26.7	52 – 57	27
Culm Grasslands	21.0 - 28.4	52 - 66	88
Ingleborough Complex	22.7 - 33.3	43 – 51	55
Mole Gap to Reigate	17.8 - 20.3	21 - 23	59
North York Moors	16.7 - 26.2	46 - 52	61
Walton Moss	17.1 - 19.8	61- 69	90

The Culm Grasslands SAC is situated in an intensive agricultural region of southwest England. The site comprises of several isolated parts separated by distances of up to 60 km. For the detailed analyses, the five clusters of the SAC that were distant from one another were assessed individually as sub-sites (Figure 5). Local wind information gathered from the nearest station (Holsworthy weather station, < 5 km from the boundary of sub-site E) suggests a south-westerly prevailing wind. Estimates of N deposition to low-growing semi-natural features at the site range from ~21 kg N ha^{-1} yr^{-1} at sub-site C to ~28 kg N ha^{-1} yr^{-1} at sub-site D (FRAME 5km grid model output for 2005). Given the large spatial variability of N at the landscape scale, the modelled N deposition values are likely to be an underestimation where there are N sources situated close to the site boundary (such as animal housing and manure spreading).

<< FIGURE 5 >>

Figure 5 – Estimated total N deposition (including oxidized and reduced N) to semi-natural grasslands in the vicinity of the Culm Grasslands Special Area of Conservation (SAC) (FRAME model output 2010), noting the sub-areas of this SAC used for local-scale analyses (cases A – E). The map also shows the locations of pig/poultry units above the threshold for the Industrial Emissions Directive (IED) that are within 10 km of the boundaries of Culm Grasslands SAC.

Further analysis of the source attribution data shows that agricultural sources are the main contributor to N deposition received by the site, comprising between 52 % (sub-site C) to 66 % (sub-site D) of N deposited (values taken from relevant grid squares covering each sub-site). The average NH_3 emission density across the whole site was estimated at 16 kg N ha^{-1} yr^{-1}, with emissions ranging from ~9 - 30 kg N ha^{-1} yr^{-1} between sub-sites (Figure 6). Dairy farming was found to be the largest contributor to agricultural NH_3 emissions in the 2 km buffer zone surrounding the majority of sub-sites, apart from sub-site C. Ammonia emissions associated with dairy farming are particularly variable in the area surrounding the entire site, with estimated emission densities from activities associated with dairy farming ranging between 1.2 kg N ha^{-1} yr^{-1} (sub-site C) and 22.7 kg N ha^{-1} yr^{-1} (sub-site E).

<< FIGURE 6 >>

Figure 6 – Estimated agricultural emission densities in a 2 km buffer zone surrounding the whole site and, separately, all sub-sites of Culm Grasslands Special Area of Conservation (SAC), with respect to the agricultural emission source sectors. The shading labelled "Other Livestock" refers to categories that are disclosive or contribute less than 5 % of total agricultural emissions.

A large poultry unit near sub-site C (Figure 6) is estimated to produce ~11 t NH_3-N yr^{-1} and contribute 30 % of agricultural NH_3 emissions in the area surrounding the sub-site. High-resolution (1 km grid) estimates of NH_3 concentrations show 'hot-spots' surrounding a number of IED units upwind (southwest) of sub-site D (where sub-site estimates of N deposition are highest).

Google Earth imagery (imagery date 31/12/2010) indicates agricultural emission sources close to the site boundaries of sub-site B and D, with cattle grazing in fields adjacent to the sites. There also appears to be an uncovered slurry lagoon next to sub-site D, though discussions with the site officer responsible for the SAC confirmed that the lagoon was no longer active.

At sub-sites D and E, local management data from site officers were used to produce more detailed site-specific emission estimates, for comparison with the estimates produced using national data and average UK EFs from Misselbrook *et al.* (2013). The two sets of emission estimates were very similar, with estimated emissions being 3 % and 1 % smaller than the UK average estimates at sub-sites D and E, respectively. The modest difference between the estimates was due to a shorter housing period than the UK average (i.e. resulting in lower emissions), offset by limited opportunity for rapid incorporation of manures due to the predominantly grassland-based agriculture (i.e. resulting in increased land spreading emissions).

3.4. Comparison between Culm Grasslands SAC and other local scale assessments

One of the sites assessed in more detail is North York Moors SAC, a large site (440 ha) that Intersects forty-seven 5 km by 5 km source attribution grid squares. The source attribution dataset estimates that agricultural sources contribute ~46 - 52 % of the total N deposition received by the site. The estimate in the national scale analysis is given as 52 %, which corresponds to the single grid square with the highest estimate of N deposition, rather than providing a range for the whole site, to assess spatial variability. The source attribution dataset also indicates that a high proportion of the N deposition received by Mole Gap to Reigate Escarpment SAC and Ingleborough Complex SAC are from agricultural emission sources. However, the analysis of agricultural emission densities for the immediate area around these sites shows relatively low values. This would suggest that agricultural N deposition received by the sites is coming from further afield, therefore targeting local agricultural sources at such sites is not likely to substantially reduce N deposition at the site, and efforts to reduce N deposition regionally/nationally/internationally are therefore needed to achieve lower N deposition.

In the same way as for Culm Grasslands SAC, agricultural emissions at Cerne & Sydling Downs SAC (situated in SW England) were also estimated using local management practice data rather than national average data. At this site, agricultural emissions were overestimated by 11 % using UK average EFs, compared with emissions estimated with local management data. The overestimate from average UK EFs can be attributed to a shorter than average housing period for beef cattle in the area (associated with lower housing emissions). The lower emissions from beef cattle are partly offset by higher emissions from dairy cattle in the area, due to a greater proportion of slurry being stored in slurry lagoons (associated with higher emissions due to larger emitting surface areas) rather than slurry tanks or weeping-wall storage than on average across the UK.

4. Discussion

4.1 National scale approaches

This study showed that it is possible to identify the main source categories contributing to N deposition using the national scale UK source attribution dataset (e.g. Bealey *et al*. 2014). However, this dataset did not allow for the differentiation between deposition that originated from local emission sources (i.e. those within 2 km of the site boundary) and those located further afield (> 2 km from the site boundary). In the source attribution dataset, agriculture is given as a single category (due to data confidentiality and disclosivity issues), so that more detailed sector-specific analysis of agricultural NH_3 emission estimates was necessary to identify key agricultural activities, (such as dairy farming) around each site.

The national scale analyses described here provide useful information that could be used by site officers to select potential NH_3 mitigation at designated sites. There are however, certain limitations with a national scale analysis, which need to be taken into account when interpreting the data on an individual site basis. For example, in the present implementation of this approach, the UK source-attribution dataset is valid for the year 2005 and consequently does not include emission sources that postdate the analysis and sources that have since been included into the emission inventories (e.g. anaerobic digestion). The relative contributions to N deposition may therefore have changed over the recent decade, with e.g. current agricultural activities intensified/extensified in some areas since 2005. The national scale methodology also assumes N threats are homogenous across sites, however it is important to note that some English SACs have an expansive site area (with some > 400 km^2), and therefore N threats will be highly variable across such sites. For example, agricultural emission densities and dominant agricultural sectors are likely to vary substantially over such large areas. The average N deposition estimates and agricultural emission densities for these sites should therefore be treated with caution, as substantial emissions across parts of the surrounding areas may have been compensated with very low emissions elsewhere.

Spatial variability of N deposition within a 5 km grid square may be very large, for different reasons, which may result in grid square estimates over- or under estimating true deposition. Firstly, this may be due to high spatial variability in local emissions and dry deposition. For example, local emission hotspots in a lowland landscape (e.g. farms) may lead to large concentration and dry deposition gradients away from the source (also depending on land use-related surface roughness, canopy compensation point i.e. relative N concentrations of the plant surfaces vs atmosphere). Secondly, this may be due to high spatial variability in wet deposition. In the UK, wet N deposition across a 5 km gridsquare (potentially originating from distant sources) may vary substantially, depending on topography, with altitude/rain shadow effects influencing deposition, but less related to local sources.

The spatial location of the farm data used are in some cases derived from postcodes and therefore may be several 100 m (in some rarer cases up to 1-2 km) away from the true source location. In terms of uncertainty, agricultural holdings were treated as point sources, rather than area sources, which means emissions from an entire farm are attributed to a single spatial location. A farm's main livestock housing may therefore be situated away from the given point location and incorrectly included/excluded from emission estimates. However, given the number of farms included in the calculations at each SAC, this is not thought to contribute substantially to the uncertainty in emission density estimates. Such issues could easily be resolved locally at a detailed consultation.

For countries where source attribution estimates do not currently exist, these can be derived with openly available emission maps. Emission data (separate for source categories such as agriculture, industry, road transport) are available from open source international data collections such as the Centre on Emission Inventories and Projections data portal (http://www.ceip.at/webdab-emission-database). Deposition can then be estimated from these emission maps using an atmospheric transport model. In this study, the FRAME model has been used for the UK, which can be set up relatively easily for other domains (e.g. Poland, China – Werner *et al.*, 2016; Zhang *et al.,* 2011).

4.3. Combination of national and local-scale information

The detailed site-level analysis indicated that the source attribution dataset was able to characterise the main source sectors contributing to N deposition successfully. This is in spite of relatively large known uncertainties associated with the modelled deposition estimates (e.g. Dore et al. 2012). The input data used to produce the source attribution data are relatively coarse: the modelling uses UK average meteorological conditions (e.g. precipitation rates and wind direction) and emission estimates at a 5 km grid resolution. One limitation of the source attribution dataset is that it is not possible to distinguish between N deposition threats from local sources, or from medium/long-range transport. Sites may therefore be estimated to receive a substantial proportion of N deposition from a particular source category (e.g. agriculture), but this may originate from a range of distances from local to transboundary. The detailed site-level assessment is therefore necessary to determine if local measures can provide reductions in atmospheric N input to a site.

In terms of quantifying agricultural NH_3 emissions, the use of average EFs in agricultural emission estimates also forces the assumption that every farm follows average management practice, in this case for the whole of England, which may lead to under/over estimates of NH_3 emissions at a local level. This was investigated in more detail for a small number of SACs where local agricultural practice information was available, with an estimated margin of error of +/- 3% at Culm Grasslands SAC and 11% at Cerne and Sydling Downs SAC. If mitigation measures are already implemented in an area, the associated reductions in local emissions are unaccounted for in the analysis, which again emphasises the need for further information from and discussion with local stakeholders, following initial national-level screening. Given the uncertainties associated with the national scale assessment, further site-specific analyses are therefore considered essential for selecting and targeting specific and locally relevant NH_3 measures.

The identification of the main agricultural sources contributing to N deposition and elevated NH_3 concentrations at a site is a first step towards pinpointing the most effective locally suitable N mitigation measures. As individual mitigation measures may only be appropriate to certain agricultural sectors, or only for suitable soil conditions, assessing geographically separate areas individually is expected to lead to improved targeting of measures. The results of the detailed site analyses provided useful information to supplement the national scale analyses. For example, examining NH_3 concentrations and aerial imagery for each site, in combination with statistics on wind direction, allowed sources upwind of site boundaries to be identified and prioritised for potential spatial targeting of measures. Further steps towards implementation of such measures could then prioritise targeting in collaboration with the local community and stakeholders, as has been proposed by Natural England, the relevant conservation agency (Site Nitrogen Action Plans, SNAPS, Natural England, 2015).

2. Conclusion

The results of this study demonstrate that by using a combination of national datasets (e.g. atmospheric N concentrations and deposition maps), and high-resolution agricultural census/survey data, it is possible to identify suitable measures to reduce N deposition from agricultural sources. The present assessment was conducted for the example of England, accounting for 240 Special Areas of Conservation (SACs) in the Natura 2000 network, demonstrating the wider relevance of the approach, which is applicable to other regions. Although national scale datasets can provide information on general N deposition threats at the landscape scale, we have also shown that additional local-scale information is required to understand the feasibility of proposed mitigation measures and their impact on N deposition at this scale. Incorporating local agricultural management data, such as animal housing systems, duration of housing periods, and existing mitigation measures into emission estimates, is shown to be especially important for quantifying the main agricultural emission sources close to designated sites. For example, local information on cattle housing periods at one of the study sites improved emission estimates by 3 to 11%, compared with national average estimates. The approaches developed here provide a foundation to support conservation officers and government agencies in identifying of suitable mitigation measures to reduce atmospheric N deposition received by sensitive habitats.

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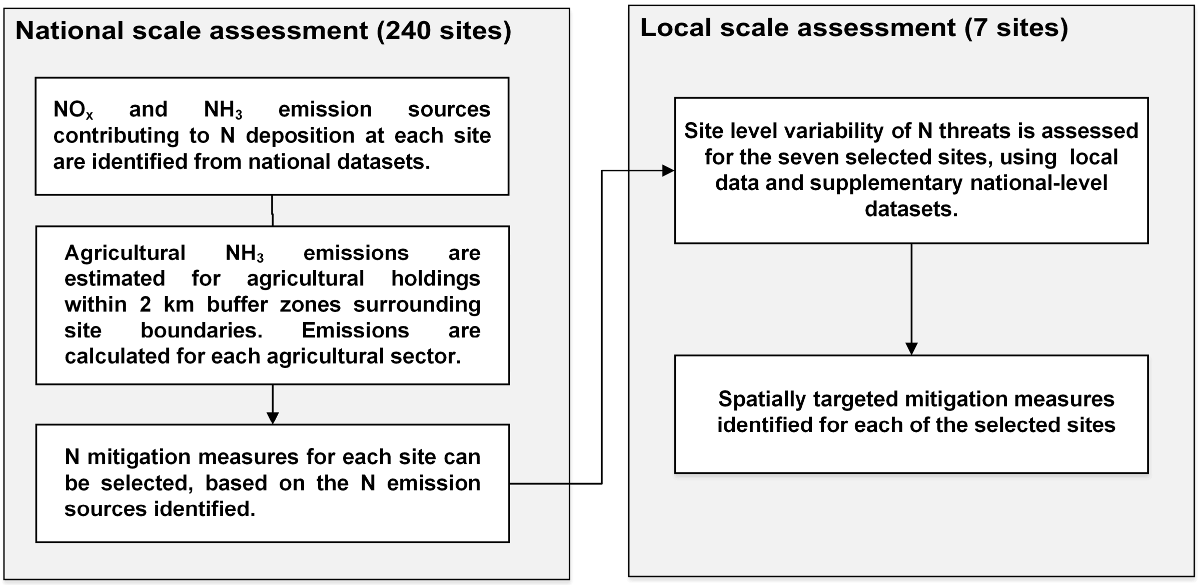


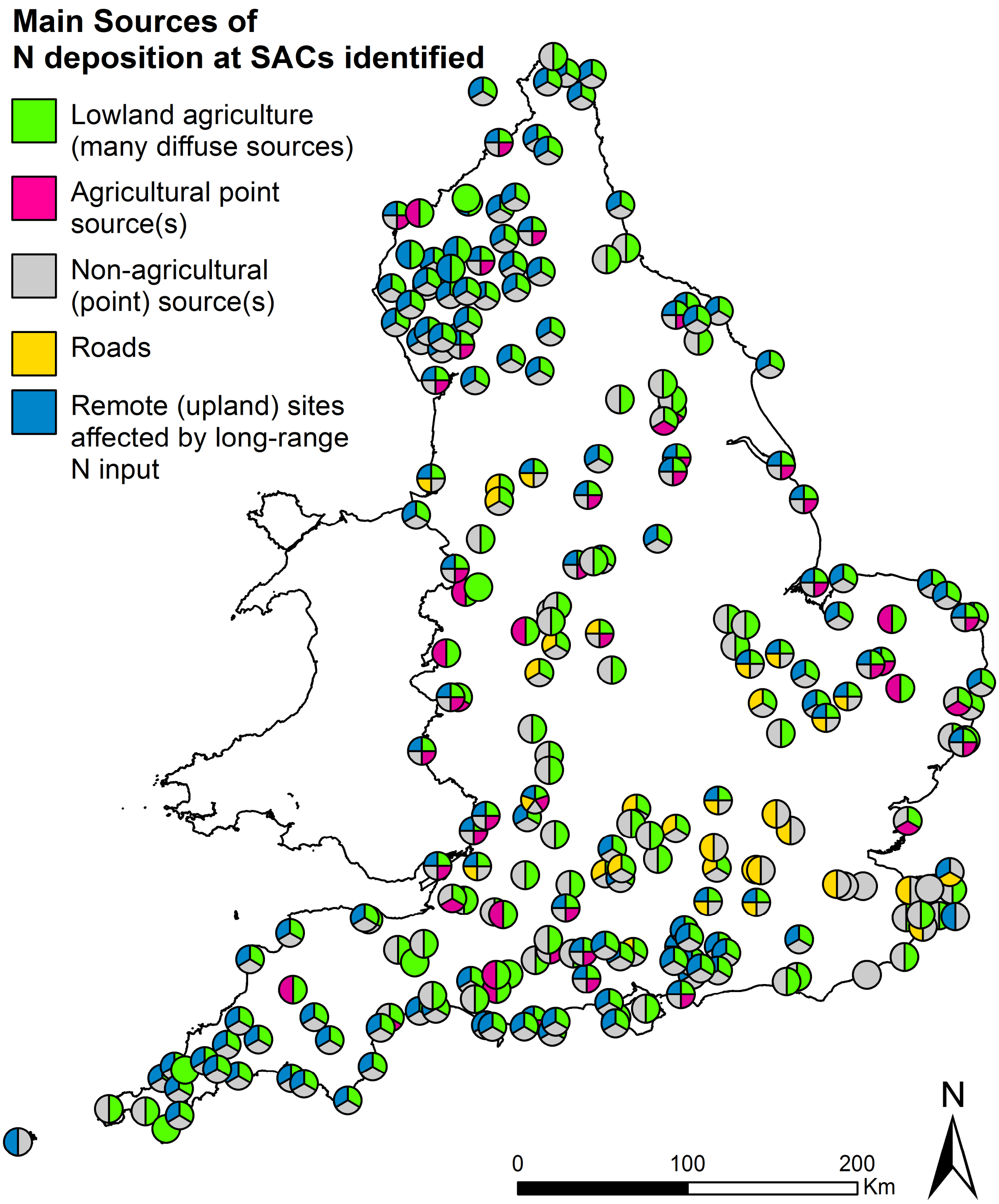
NO_x and NH_3 emission sources contributing to N deposition at each site are identified from national datasets.

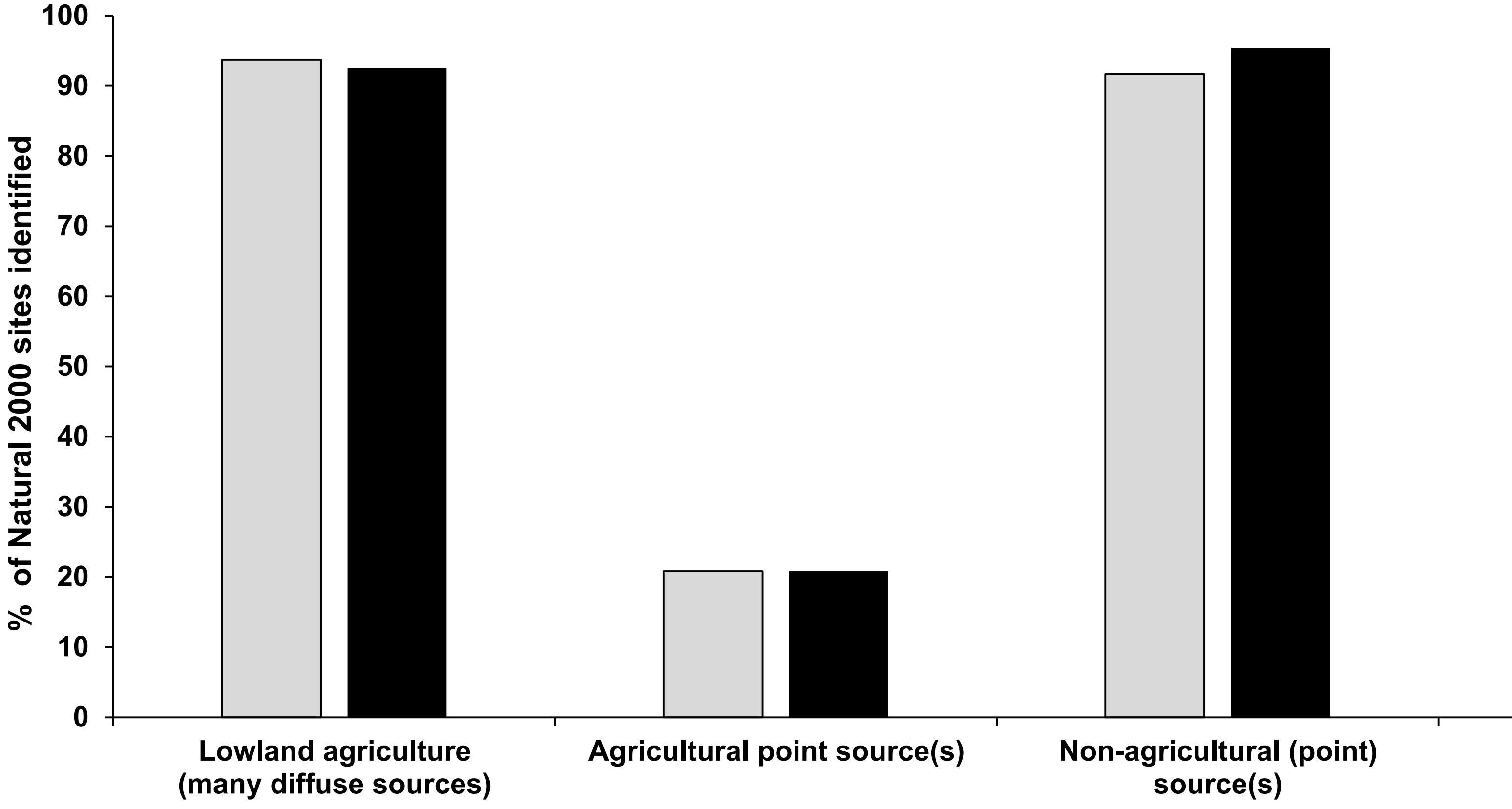
Agricultural NH_3 emissions are estimated for agricultural holdings within 2 km buffer zones surrounding site boundaries. Emissions are calculated for each agricultural sector.

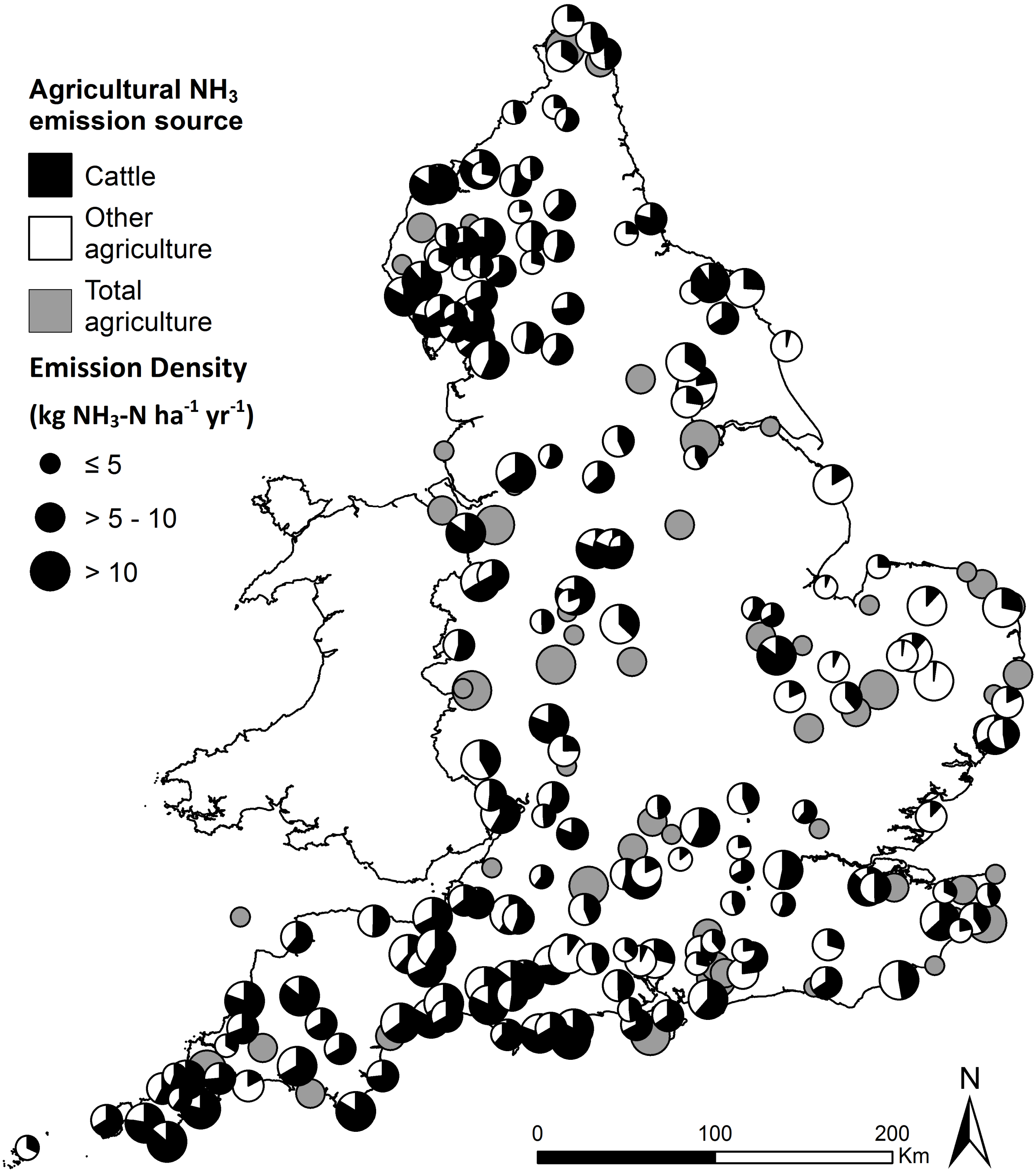
N mitigation measures for each site can be selected, based on the N emission sources identified.

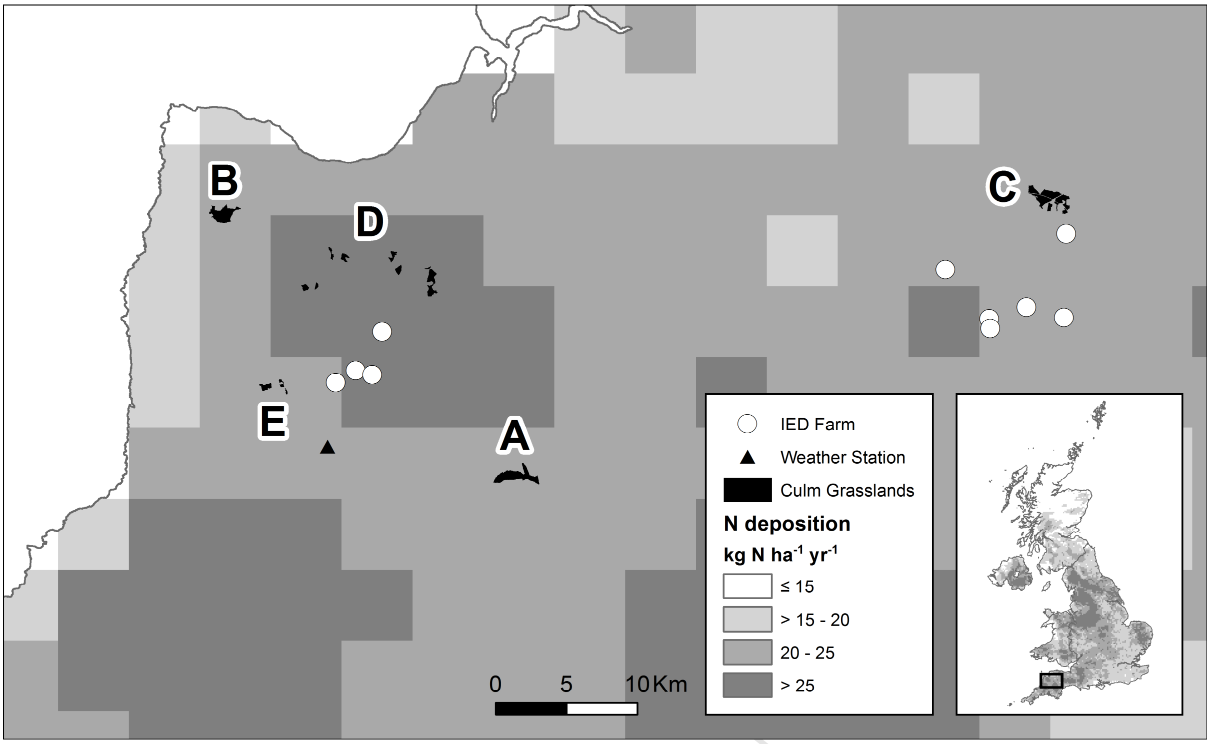
Site level variability of N threats is assessed for the seven selected sites, using local data and supplementary national-level datasets.

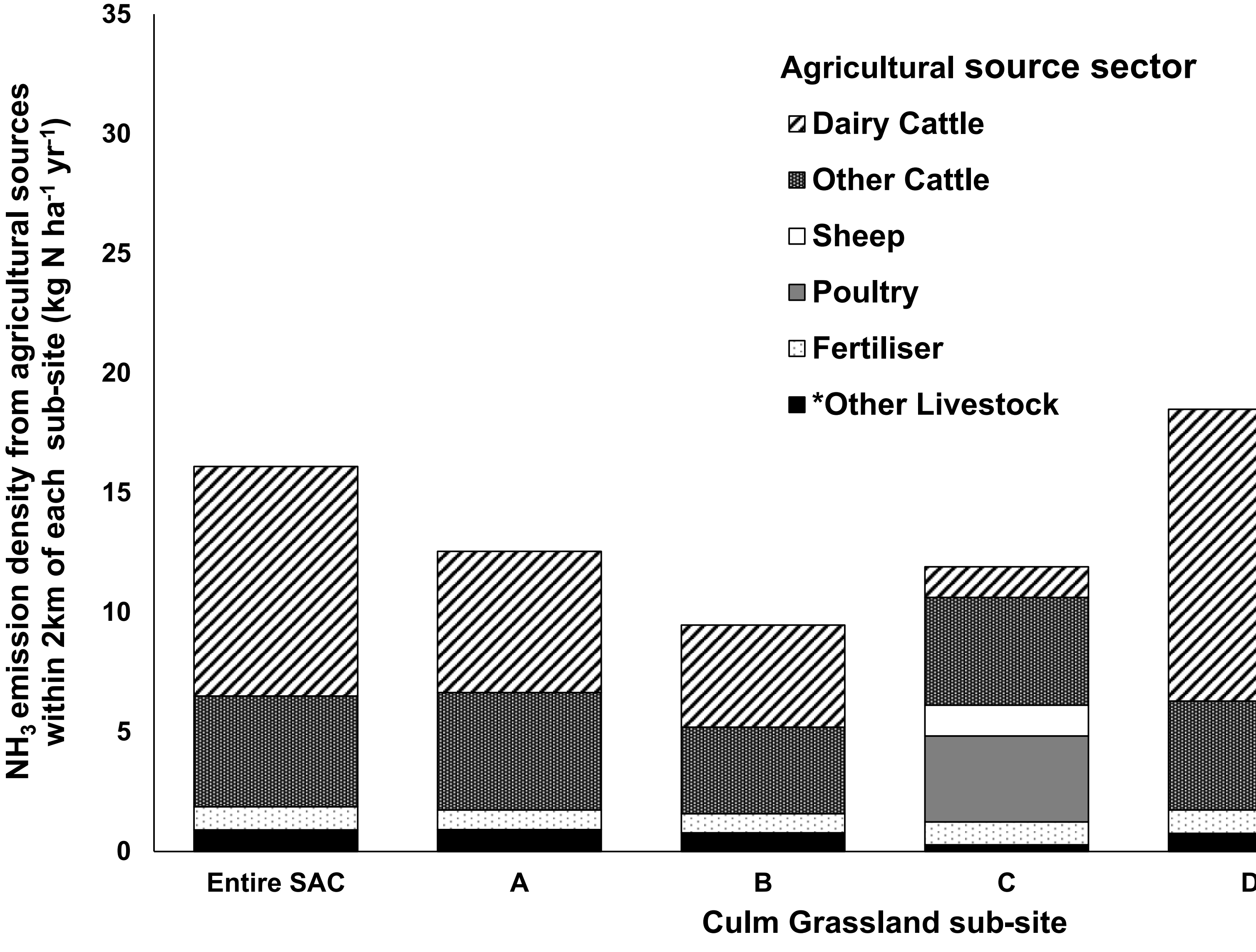
Spatially targeted mitigation measures identified for each of the selected sites


Main Sources of
N deposition at SACs identified
🟩 Lowland agriculture (many diffuse sources)
🟥 Agricultural point source(s)
⬜ Non-agricultural (point) source(s)
🟨 Roads
🟦 Remote (upland) sites affected by long-range N input
0
100
200
Km
N


100
90
80
70
60
50
40
30
20
10
0
% of Natural 2000 sites identified
Lowland agriculture (many diffuse sources)
Agricultural point source(s)
Non-agricultural (point) source(s)


Agricultural NH_3 emission source
Cattle
Other agriculture
Total agriculture
Emission Density
(kg NH_3-N ha^{-1} yr^{-1})
≤ 5
> 5 - 10
> 10
N
0
100
200
Km


A
B
C
D
E
IED Farm
Weather Station
Culm Grasslands
N deposition
kg N ha-1 yr-1
≤ 15
> 15 - 20
20 - 25
> 25
0
5
10Km


35
30
25
20
15
10
5
0
NH$_3$ emission density from agricultural sources within 2km of each sub-site (kg N ha^{-1} yr^{-1})
Agricultural source sector
▨ Dairy Cattle
▩ Other Cattle
☐ Sheep
■ Poultry
⬚ Fertiliser
■ *Other Livestock
Entire SAC
A
B
C
D
Culm Grassland sub-site

- An approach to identify suitable NH_3 mitigation measures is proposed
- The methodology combines emission, concentration and deposition data
- Agriculture contributes ~45 % of total N deposition received by SACs